Assessment of the MINOS Steel Design and Construction Far Detector at Soudan Mine[1]

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Summary
The assembly of the MINOS far detector steel was nearing completion[2] and the original design engineers, shown in Figure 1, were tasked to assess the construction of the steel planes. This assessment included observing the hanging of plane # 483 on May 29, 2003 and a visual inspection of the *as built* Super Modules SM1 and SM2. Neither the building of a plane, nor the moving of steel from the surface was observed since plane no. 483 was assembled prior to our arrival and the steel to assemble the remaining planes had not yet been delivered by the vendor. Super Modules, SM1 and SM2 were completed on time, on budget and with an impressive safety record of no lost time due to lifting and hoisting operations. There were 6 items noted during the visual inspection of the hanging planes and will be discussed below. These items may have been discussed in other documents, but this report takes the opportunity to readdress them.

Figure 1 Tony Ladran, LBNL (left) and John Alner, RAL (right) at Soudan Mine MINOS assembly area

Description

In designing the MINOS steel several full-scale prototypes were built at Fermi Lab from 1999 to 2001 to characterize single plane[3] and multiple plane[4] behavior. These prototypes were invaluable in developing assembly techniques, detector integration and installation procedures. These procedures were implemented while building MINOS Far detector. The detector shown in Figure 3 is comprised of two Super Modules (SM1 and SM2) with a total of 486 steel planes, 484 with scintillator modules (the first plane in a super module has no scintillator). SM1 contains planes #0 to #248. SM2 contains planes #249 to #485. SM1 had open MUX channels and the space for more planes, hence the difference in the number of planes between the Super Modules.

The steel planes were assembled from nominally 2m x 8m x ½ inch thick AISI 1006 steel sheets plasma cut to shape and welded together to form a 1 inch thick 8m x 8m octagon. The plane was mated with scintillator modules and hung on support rails to allow the plane to hang in tension. A completed steel plane weighs about 12,000 lbs without the scintillator modules. The weight of the full assembly, shown in Figure 4, with scintillator modules, strongback and rigging is 38,300 lbs. Bolting it to the adjacent plane using axial bolts and a center collar provides the structural stability of a plane. The axial bolts are anchored to the first plane of a super module, which is attached to a steel bookend support.

There are several important features in the steel design. They include geometric parameters like maintaining the flatness of the plane and minimizing the gaps between the sheets of steel. The flatness affects the module pitch and the gap size affects the magnetic performance of the detector steel. The gaps, especially in the center region, must be minimized to provide a uniform magnetic field. The positioning and mapping of the steel and scintillator module is also important for the experimental measurements. The other important parameters are structural, for instance the stress on the ears, or the stress on the axial bolts and bookend support system. They need to be stable and assembled such that stresses are distributed as predicted. See Figure 9.

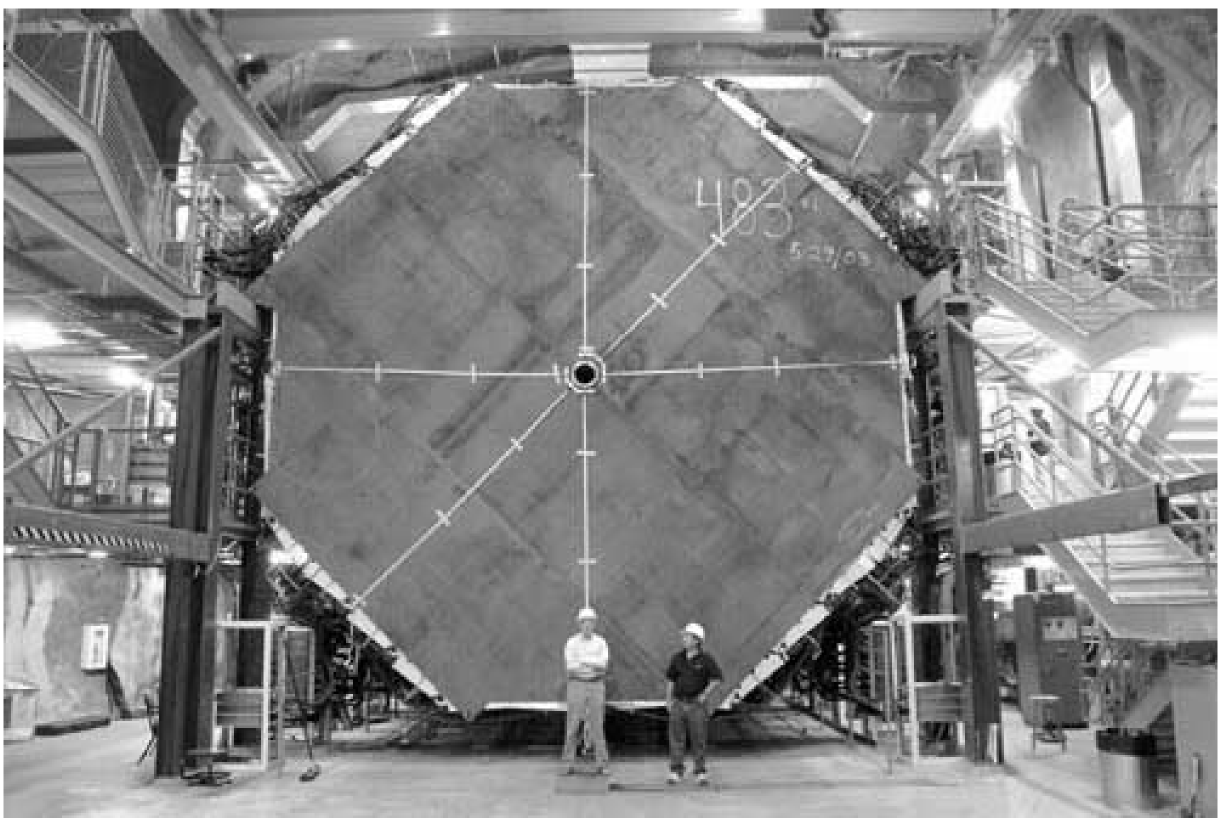

Figure 2 Plane number 483

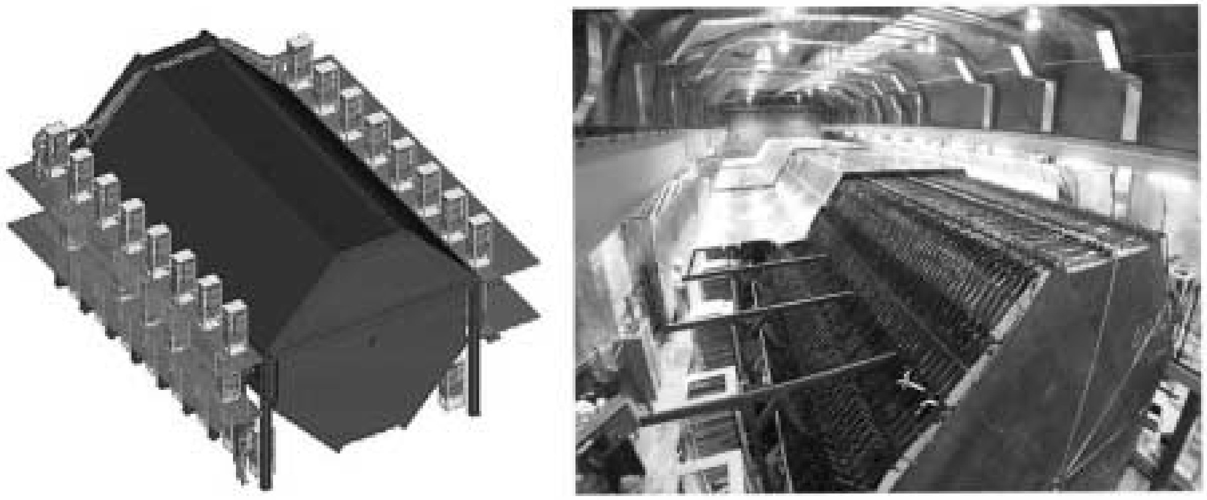

Figure 3 CAD model of Super Module with bookend (left). MINOS Super Modules SM1 and SM2 being covered with a veto shield and SM2 in foreground (right)

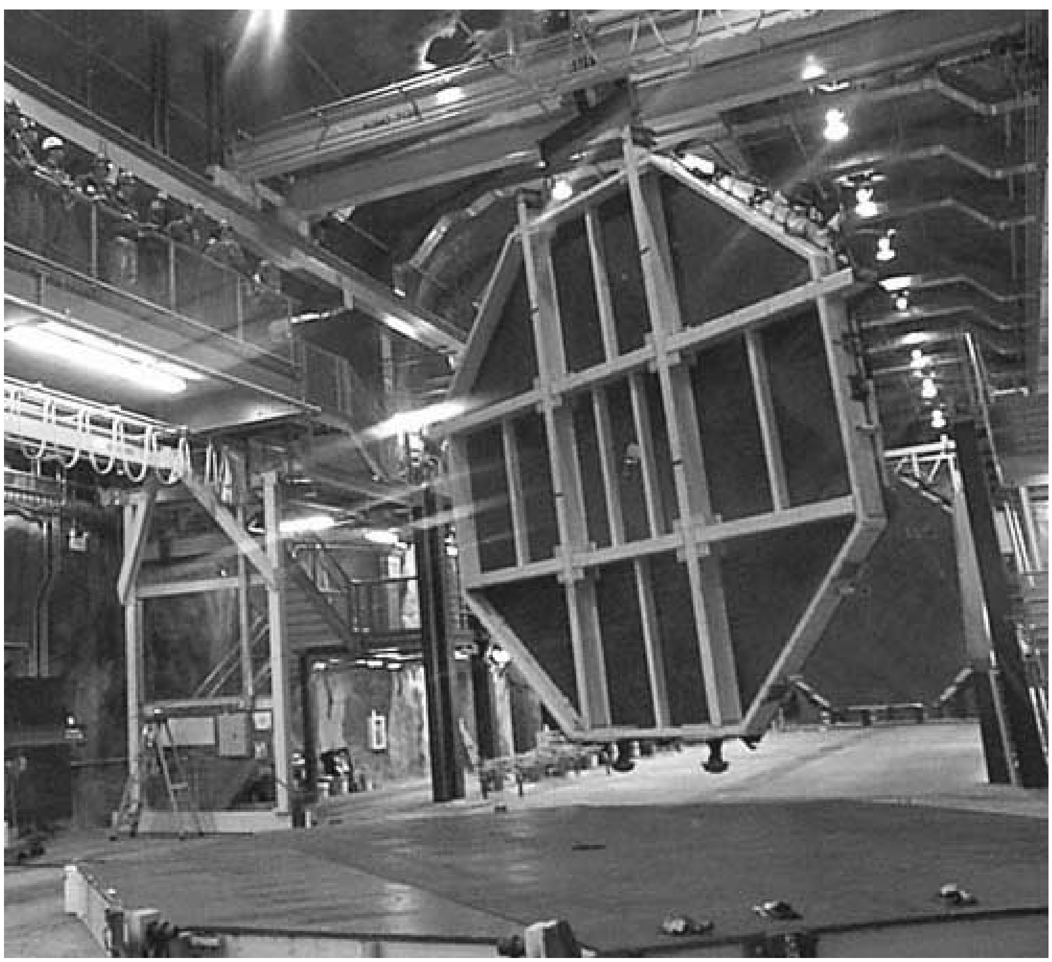

Figure 4 Strongback used to lift a single fully assembled steel plane with scintillator modules.

Observations:
In addition to observing the hanging of a plane and visual inspections of the steel mounted in the Super Modules, the observations listed below in items 1 through 6 were the results of discussions with the MINOS mine crew, staff scientist. Specific recommendations for further study are suggested for items 4, 5 and 6.

The steel planes assembly and installation procedures were reviewed with the mine crew. These procedures are documented in several NuMI notes[5 6 7] and required that the steel sheets and assembled planes be well characterized during plane construction. Each of the assembled planes were inspected and documented in plane checkout sheets. In addition, the installed position of a plane was measured using the Vulcan survey system. The Vulcan data could resolve to1mm and was used to determine warping of a plane. The survey data of SM1 is in NuMi-NOTE-GEN-866[8] and the planes in SM1 averaged a 59.49 mm/plane pitch. The survey data for SM2 is available at the mine.

1) **Steel Flatness** - The steel sheets supplied by Olympic Steel were consistent in flatness. They met specifications in all but 2% (about 50 of 3888) of the steel sheets delivered to the mine. The majority of the out of tolerance sheets were in the shipments at the end of the build of SM2. About 90% of the sheets were brought back into specifications by mechanically flattening them in the mine.

2) **Floor Bulge** - The FNAL survey team performed a survey of Super Module SM1. They discovered a bulge in the floor, but based on the rest of the survey data determined that it does not affect the planes, or supports. The survey team also measured sag on the planes and found the displacement within the design specifications.

3) **Gaps in plane joints -** There were gaps, 2 mm to 4 mm, near the ears between the butted sheet joints (some as large as 9 mm were documented during assembly). This was attributed to heating and shrinkage of the ear sheets during the starting and stopping of the steel plasma cutting process. The affected edge was a distance of 2 ft. – 5 ft. within the ear.

4) **Out of plane displacement** - There was as much as a 4 mm displacement (estimated for plane #0) on the hanging planes and was most visible at the joints where the sheets were butted together. See Figures 5, 6, and 7. The source of the displacement is not known. One suggestion is that it could be a crown, or waviness in the steel sheets that could not be flattened during welding. Another suggestion is that it is caused by out of plane stresses caused when hanging the plane. In either case, it merits mentioning and further review. It is difficult to verify if this displacement is present on all the planes since only the planes exposed at the ends of the Super Modules are accessible (Plane # 0, #248, #249 and #483). Measuring the displacements on these planes was difficult due to poor accessibility so, with the exception of #483, the displacements were estimated. Using a vernier caliper the north side of plane #483 had a displacement of 2.5 mm. The displacement on #483 was visibly the smallest of the planes. Plane #248 was estimated about 3 mm and Plane #0 was estimated at 4 mm at the lower east side and 3 mm near the west ear. Plane #249 also had visible displacements, but it was not measured.

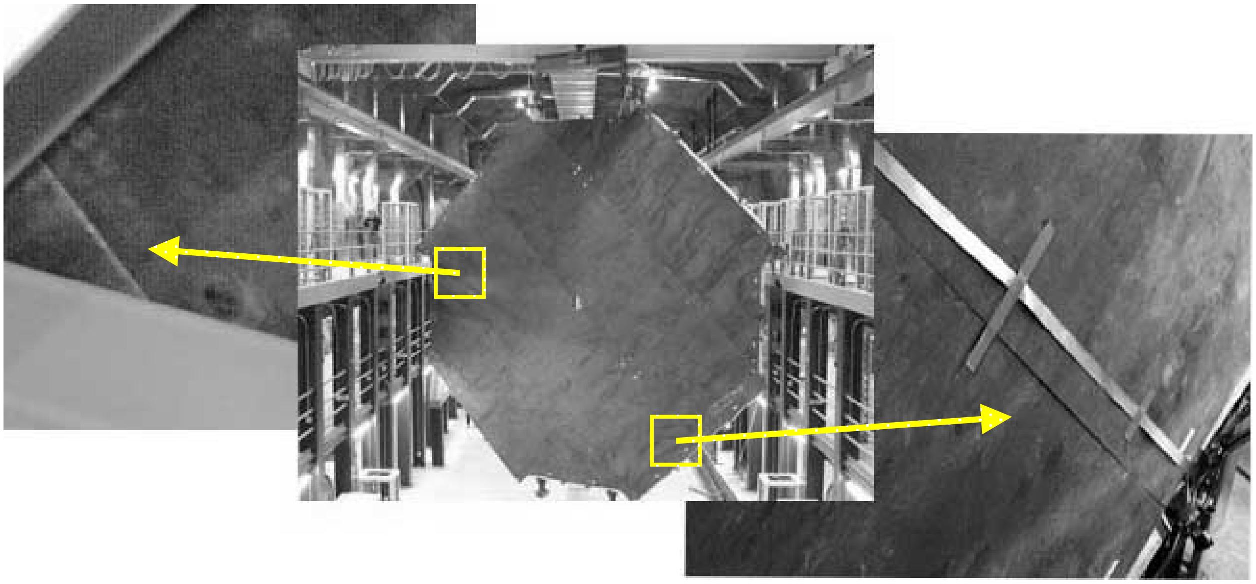

Figure 5 View North of Plane # 0 shown prior to hanging for reference (center). The out of plane displacements were found on the hanging plane mounted to the bookend support. Out of plane displacement located near the ear on the west side of plane, estimated to be 3mm (left). Out of plane displacement located on lower east side of plane, estimated to be 4mm (right).

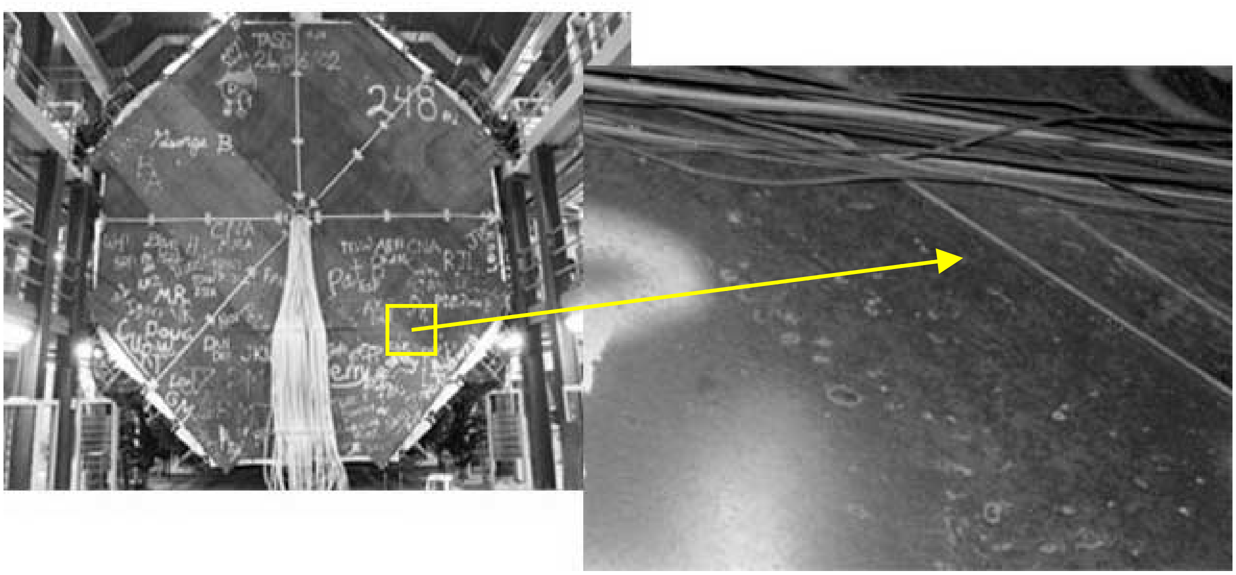

Figure 6 View of hanging Plane # 248 (left) Out of plane displacement on plane 248, estimated at 3mm (right).

Figure 7 Hanging plane # 483 (left). Measuring out of plane displacement, 2.5 mm (right)

5) **Axial Bolt Loading** – Although a bolt torque is specified, the axial bolt loading was difficult to judge during installation. It seemed that the axial bolts could be subject to additional loading if the bolt was used to draw the plane flat against the axial bolts of the previous planes. As suggested in NuMI Note L-355, the probability of failure of an axial bolt is very low if the mean is zero but the probability increases with the mean. The axial bolt load is cumulative and the mean should be verified based on the actual assembly conditions and loads. See Figure 8.

Figure 8 Ear supported on rail. Original 4-inch ear support from prototype (left). As built MINOS Super module 2 with ear supported on stainless steel bar (right)

Ear Contact Area - The contact length for the ears is shorter then the 4 inches assumed for the original LLNL stress analysis[9]. This is an improvement and is the result of a design modification to support the ears on a narrower stainless steel bar. The contact area could also be smaller due to an assembly tolerance for the ear alignment. The new stress and safety factor for the as built conditions should be recalculated, if not already done so.

a. The ears now rest on a stainless steel bar narrower than the support beam. It is used for magnetic isolation. The original ear design was on a support beam that was 4 inches wide. The narrower beam is an improved design because it does not require the ears to be precisely positioned and provides more latitude due to misalignment, or variations in the ear geometry. See Figure 8. A Finite element analysis of an ear design is shown in Figure 9, but it is not known for which support geometry.

b. It was visually observed that in some instances both steel plates that make up an ear on one side were not fully in contact with the rail. This was estimated to be true for about 5% of the planes. If the plates were not completely flat it could mean that only one plate of steel ½ inch thick instead of 2 plates of steel for a total of 1 inch thick (½ inch per steel plate) is supporting the plane. This was unexpected because after plug welding if the ears were not aligned the mine crew would grind them level to meet the specification which requires that the ears on the planes be aligned to within 2 mm or better.

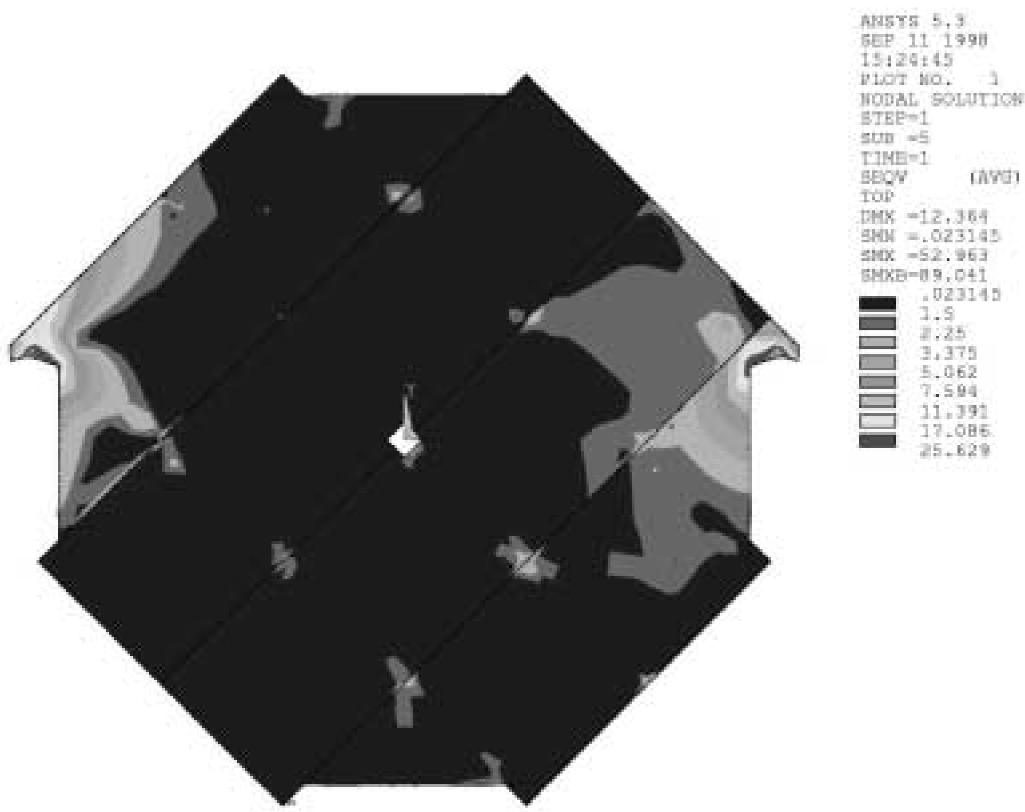

Figure 9 Early FEA Stress analysis of ears by Zhijing Tang, FNAL, 1998

Lessons Learned

The majority opinion about the building of the MINOS detector steel is that it went together as predicted. The extensive preliminary work done with the full-scale prototypes in developing the assembly procedures and designing the steel handling fixtures is what made that possible. The average plane build rate over the entire project was 5.91 per week working two shifts. This was as high as 6.5 planes per week for SM1, which went very smoothly and had good material. The build rate dropped during SM2 where problems with material slowed things down. If there was a delay of any sort in the construction of the plane it impacted several areas causing timing conflicts that were difficult to work around.

The importance of good material and quality control became apparent during the build of SM2 when steel was received that was out of tolerance (not flat). When this occurred the bottlenecks that are inherent to building in the limited space of the mine with a just-in-time process became apparent. This manual rework could take several hours and would hold up the process flow. In a few cases some steel was not repairable and needed to be sent back to the surface. Handling single pieces of steel and returning it to the surface required special handling and could tie up several of the crew and further impact plane production. The impact was compounded since it would leave an incomplete bundle in the mine that had to be dealt with. This experience with the out of tolerance steel emphasized the necessity to assure that the materials meet specification even before they reached the surface building. The process was very sensitive to material flow. Even with less than 2% of the steel being out of tolerance the build rate was impacted.

Plug welding, crane availability and surveying were other segments of the build process that had experienced bottlenecks. Since there was only one plug weld machine there were times construction on one of the planes had to stop while it waited to be welded. This task took 3-4 hours depending on the flatness of the steel resulting in a standing army effect of an entire crew of 4 for this time period. The other bottlenecks, hanging the plane and surveying were closely coupled since there is only 1 large overhead crane and one man-lift for survey work on planes providing another 3-4 hour window that could cause a standing army effect.

Conclusion

With the exception of the out of plane displacement discussed in item 4, there were not any major surprises. It is not known at this time if the out of plane displacement were measured after a plane was hung. It may have been previously examined and acceptable values determined. If they have been, the documents should be reviewed and included in a supplement to this report. If not, it is recommended that some effort be made to make a qualitative assessment of this and the other observations noted below.

It should be noted that the mine crew worked hard to maintain consistency in the assembly process. There were many parameters during assembly that needed to be controlled to build the planes in a consistent manner. It was necessary to minimize the sheet gaps to provide a uniform magnetic field. For structural integrity and stability it was necessary to minimize stresses induced from the hanging process. This includes proper loading on the ears and the axial bolts. Although, issues were brought up pertaining to the sheet-to-sheet gaps, the ear stress and the axial bolt loading they all seen to be within the design specifications.

References

[1] This work was performed for Lawrence Livermore National Laboratory, PO B531028.
[2] The steel planes were fully commissioned. The last plane No. 485 installed June 2003.
[3] Single Plane Prototype built in Muon Lab at FNL
[4] 4PP, Four Plane Prototype built in Muon Lab at FNL
[5] MINOS Plane Assembly Procedures at the Far Detector, NuMI-Note-FD_DOCS-905
[6] Plane Installation, NuMi-Note-FD DOCS-919
[7] Procedures for Steel Material Handling, NuMI-Note_FD_DOCS-922
[8] Surveying the Construction of Super Module 1, NuMi-NOTE-GEN-866.
[9] T.Ladran, et. al., MINOS Single Plane Prototype Steel Mechanical Analysis, NuMI-L-322, Dec. 1997